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PROGRESS REPORT: GAS TURBINE REGENERATOR FOULING INVESTIGATION.

U. S. NAVAL POSTGRADUATE SCHOOL

Technical Report No. 21

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GAS TURBINE REGENERATOR FOULING
INVESTIGATION

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H. L. KOHLER AND J. A. MILLER

15 October 1964

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UNITED STATES NAVAL POSTGRADUATE SCHOOL

Monterey, California

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ABSTRACT:

A report on the progress of an experimental investigation of fouling effects in compact gas turbine regenerator matrices is presented. Fouling effects on heat transfer rates and pressure drop characteristics for a number of matrix geometries and two exhaust gas temperatures are presented. Preliminary results indicate gas side surface temperature and gas composition as the primary parameters with geometric effects occupying a lesser role. The effect of fouling on pressure drop characteristics is found to be more pronounced than the effect on heat transfer. Plans for continuation of the investigation are presented.

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I. Introduction

The present report is the first quarterly progress report on work to be carried out by the U. S. Naval Postgraduate School under sponsorship of the Bureau of Ships, Code 645. The immediate objective of this work is to evaluate the possible difficulties to be encountered in the operation of large regenerated gas turbine power plants, as occasioned by gas side fouling of the regenerator. To this end an experimental evaluation of the gas side fouling characteristics of several compact heat exchanger matrices, proposed for use in the Sea Hawk propulsion program, was begun during the first quarter of Fiscal Year 1965. Preparations for these tests had been initiated during the last quarter of FY 1964. The initial results of these tests are reported herein.

Simultaneously with a continuation of these tests, analytical and experimental studies are to be carried out in a more fundamental approach to the problem during subsequent phases of the work, with the aim of establishing engineering criteria adequate to enable the designer accurately to predict probable fouling rates under various cycle operating conditions, and probable fouling effects on overall cycle performance. This aspect of the program is intended ultimately to provide the Navy with fundamental knowledge and engineering data adequate to enable application of compact heat exchangers consonant with the most advanced state of the art, and consists of programs designed, among other things, to evaluate heat exchanger matrix performance both transient and steady state, to evaluate and optimize the performance of periodic heat exchangers, to investigate and develop new means of rotary heat exchanger

sealing, and to investigate thermal stress effects in compact heat exchanger matrices.

The goals set for Fiscal Year 1965 are primarily the resolution of the fouling problems utilizing the existing test rig, plus an additional parallel component now designed; the establishment of a large heat exchanger test apparatus for the evaluation of newly developed matrices; and the extension of a previously undertaken analysis of rotary heat exchanger performance. The possibility of completing these, or of adding new taks, is of course contingent on staff availability and on the rate at which the technical problems posed by the immediate goals are resolved.

II. Present Status of Program

The present state of the facility includes an active and thoroughly instrumented rig for the evaluation of regenerator matrix fouling performance, installed in the turboprop cell of the Department of Aeronautics, and shown in Figures 1 and 2. A segmented counter-flow heat exchanger designed to run in parallel with this fouling unit is under design and construction. A large air-to-steam rig for evaluating heat exchanger performance of larger-sized test matrices is also under construction. The fouling rig has already produced substantial engineering information.

The fouling rig is shown diagramatically in Figure 3 and consists of an Air Research Corporation GTC 85-90 gas turbine compressor as a turbine exhaust gas source, a large fixed air supply to the cooling side of the small test matrices, and associated duct work and instrumentation.

The gas turbine compressor is capable of delivering up to 210 lb/min at turbine exhaust temperatures from 600° to 1200°F. Turbine exhaust temperature is controlled by varying compressor bleed air flow, and there is provision for by-passing any portion of the turbine exhaust products, thereby permitting independent control both of gas side temperature and of mass flow rate. The fuel employed is marine diesel oil MIL F-16884D. Cold-side air is provided by a large fixed compressor, existing in the laboratory primarily to provide jet engine starting air; mass flow rates of up to 100 lb/sec are available, and aftercoolers and a gas-fired heater allow control of delivery temperatures from about 90°F to 1000°F at full mass flow. The duct work is adapted to test as many as three 6-inch cubic matrix modules simultaneously in cross counterflow. A typical module is shown in Figure 4. Instrumentation is provided for continuous monitoring of heat exchanger effectiveness and pressure drop characteristics of each of the test modules, as well as for monitoring performance of the gas turbine and air supply. Figure 5 shows three typical modules installed and instrumented. Because turbine exhaust gas content had been demonstrated by early results to be of prime significance to the fouling rate, the presently installed conventional combustion analyzers will soon be augmented with an elaborate gas chromatograph to provide a more sophisticated analysis of turbine exhaust products.

Establishment of a segmented, counterflow, annular type heat exchanger to be run in parallel with this present fouling rig was also dictated by results obtained from the early runs. The new test section, shown diagramatically in Figure 6, will permit the quantitative evaluation of fouling rate directly as a function of surface temperature, with

independent control of gas stream velocity, heat transfer rate, gas temperature and turbine exhaust gas content. This has been deemed an appropriate and meaningful method of obtaining fundamental information on fouling rates, since results to date with a variety of heat exchanger matrix configurations have indicated that, except for surface density, core geometry is a relatively insensitive parameter. Thermocouples and heat flow meters will provide means for continuously monitoring the local heat transfer performance; and disassembly of the segmented unit will provide means for local evaluation of the rate of fouling deposition.

The large heat exchanger evaluation rig, now under construction, is located in the laboratories of the Mechanical Engineering Department in order to be close to the base steam plant, which will provide unlimited saturated steam for test purposes. The air side will be capable of providing up to 6000 CFM across pressure drops up to 5 psi. Complete instrumentation will be available for the evaluation of heat transfer and pressure drop characteristics of compact heat exchangers, including very large cores. This project is approximately 50% complete, and approximately one half of the budgeted funds have been committed. It is expected that no difficulty will be presented to the current objective of having this facility operational in FY 1965. Expansion of this facility, employing the same air and steam supplies, to permit evaluation of periodic heat exchangers, and to provide transient response capability, is planned to include not only heat transfer and pressure drop instrumentation but also thermal stress instrumentation.

III. Fouling Results

The first fouling run was made at a relatively low turbine exhaust temperature, 650°F, and resulted in severe fouling in the first 5 hours running time. The heat transfer and pressure drop characteristics from Run I are presented in Figure 7. Inlet temperatures to downstream modules 2 and 3 were in the ranges 285-425°F and 180-320°F respectively, rising progressively from the lower to the higher figures with time. (Operating conditions for each run are summarized in Table I). The initial figures imply, of course, a high rate of heat transfer in the upstream modules, which diminishes with increased fouling and leads to the rise in inlet temperatures for the second and third modules. With this rising inlet temperature there is a decreasing rate of loss of performance: as might be expected, the lower the average gas temperature the greater the fouling rate. A somewhat surprising result, however, appears in the pressure drop characteristics, which show large and continuously increasing rates of degradation. It might be expected that a relatively thin deposition of carbonacious matter over the surface of the heat transfer matrix would tend to have a more dramatic effect on the heat transfer effectiveness than on the pressure drop characteristics. This, however, is not borne out by the results of Figure 7. Physical examination of the modules, and particularly of module 1 upstream, shown in Figure 8, gives some insight into these results. In Figure 8 there is substantial evidence of partial blockage at the upstream face, which is probably responsible for an appreciable portion of the total increase in pressure drop; but from the downstream side, as shown in Figure 9, it is apparent that the upstream depositions are not typical

of the entire core passage, that is, the passages are not blocked along their length to the extent indicated by the upstream face, Figure 8. In fact, examination of the passages reveals only a relatively thin carbonacious deposit, uniformly distributed over the surface, downstream of the face. With these observations in mind, there are a number of possible explanations for this curious relative effect of fouling on heat transfer and pressure drop. Examination of the usual friction factor vs. pressure drop relationship demonstrates that the pressure drop is very nearly inversely proportional to the hydraulic diameter to the 4.5 power. Hence any small change in hydraulic diameter, such as might be occasioned by a relatively thin deposition, may indeed have a radical effect on pressure drop. Moreover the nature of the deposit is such that the emissivitity of the surface may be materially improved, enhancing heat transfer by radiation. This effect would tend to mitigate the decrease in heat transfer occasioned by the conductive resistance of the film itself. Resolution of these questions is dependent upon the determination of the thermal characteristics and thicknesses of the depositions, and is one of the objectives of the segmented counterflow heat exchanger program.

Runs II, III and IV were made at a significantly higher level of turbine exhaust temperature than was Run I. These three runs were made with similar gas and air inlet temperatures, but with different module designs, all of modern compact construction. The heat transfer and pressure drop results of Run II are summarized in Figure 10. Inlet temperature to the first module was 1025^{o}F, to the second and third, 760^{o}F and 580^{o}F, respectively. Effectiveness (see Table I, page 13) was

approximately 60% for the three modules. The long-term (22 hours) heat transfer effect of fouling was negligible, and only a minimal increase in friction factor was obtained. The increase in friction factor was greatest for the coolest module, and least for the hottest, as would be expected.

The heat transfer and pressure drop results of Run III are summarized in Figure 11. Inlet temperature to the first module was approximately 1050^{o}F. Inlet temperatures to the remaining two modules were approximately 775^{o}F and 600^{o}F, respectively. Effectiveness ranged beween 50% and 70% for the three modules. Relatively minor effects on heat transfer and pressure drop characteristics were occasioned by fouling. In fact, small changes in operating parameters during a run, including turbine operating conditions, probably constitute the major reason for the erratic behavior of the friction factor and heat transfer coefficient. A buildup and subsequent blowing away of fouling deposits may also contribute to this erratic behavior.

The heat transfer and pressure drop results of Run IV are summarized in Figure 12. Inlet temperature to the first module was approximately 1025^{o}F. Inlet temperature to the second and third were 850^{o}F and 690^{o} respectively. During the first 12 hours of running the results appear to be moderate and typical of the other high temperature runs; the greatest fouling effects occurring to the coldest module, and the least fouling to the hottest module. Some time during the period subsequent to the twelfth hour, an oil seal leak developed in the gas turbine compressor, leading to very substantial heat exchanger fouling which was not detected until shutdown after 32 hours. The gas turbine unit has been returned to the manufacturer for repair and the estimated down time is thirty days.

Experience with cleaning methods has been restricted to two processes. After Run I the test modules were cleaned ultrasonically with a detergent water mixture, and excellent results were obtained. After subsequent runs, the modules were cleaned by shutting off the cold-side airflow and running the modules in place with a gas side inlet temperature of approximately 1000^{o}F. Again, excellent results were obtained, in a very short time, and the cleaned matrices appeared to be like new in every way, with the exception of some slight oxidation inherent to high temperature operation. It would appear that, at least for moderate fouling, effective cleaning can be obtained by bypassing the cold-air-side flow for brief periods. Again, in order to obtain quantitative engineering information, a simple experiment employing the proposed counterflow annular rig is indicated.

IV. Conclusions, and Action Proposed During 2nd Quarter FY '65

From the preliminary results discussed above a number of conclusions may be drawn:

1. The principal parameters affecting fouling rates appear to be gas side surface temperature (indicated roughly by average gas side fluid temperature) and exhaust gas composition. The effect of matrix geometry appears to be secondary, and principally related to heat transfer surface density. Stagnation point density does not appear to be a major parameter. Based upon this preliminary information, a requirement is indicated for a geometrically simple heat exchanger in which surface temperature, gas composition, heat transfer rate, and Reynolds numbers

may be independently controlled and monitored. The requirement of more detailed knowledge concerning gas compositon has dictated a substantially more sophisticated approach to the determination of gas side composition, which it is felt will be provided by a gas chromatograph.

2. Because of some surprising results with respect to pressure drop increase relative to heat transfer performance, more fundamental engineering information is necessary to an understanding of the exact mechanisms by which fouling affects these two performance parameters. It is possible that in this area surface geometry may play an important role. It is expected that results of the simple-geometry counterflow heat exchanger program will provide considerable insight into this problem area.

3. Assuming that for a given application it is not possible to avoid completely those operating conditions under which moderate fouling occurs, cleaning and restoration of original performance can be obtained by relatively simple means, such as bypass of regenerator air coupled with turbine exhaust temperatures of the order of $1000^{o}F$. Radical procedures such as flushing or reverse flow operation do not appear necessary.

4. Coordinated with this type of fouling information, and with the results of the contemplated counterflow heat exchanger program, a simultaneous analytical program should be undertaken for the purposes both of augmenting the experimental work and of suggesting other avenues of investigation.

5. During the second quarter, FY 1965, work will continue with the small modules in the present fouling rig, augmented by studies in the segmented simple-geometry side rig when it becomes available. This work will continue to be directed by Professors Kohler and Miller on a half-time basis. An analytical program will also be inaugurated, time permitting. Professor Pucci is supervising the design and construction of the large heat exchanger rig, in addition to his full-time academic duties.

Table 1

Summary of Experimental Operating Parameters

Run 1 Hamilton Standard Matrices

Module	1	2	3
Module Identification	Fine	Coarse	Fine
Gas Inlet Temp. (^{o}F)	650	425-285	320-180
Gas Outlet Temp. (^{o}F)	425-485	320-180	185-105
Gas Side Face Velocity (Ft/Sec)	44-16	37-11	35-10
Cmin/Cmax	0.99-0.36	0.99-0.35	0.99-0.34
Effectiveness	0.61-0.64	0.60-0.62	0.61-0.62

Run 2 Air Research Matrices

Module	1	2	3
Module Identification	Fine	Fine	Coarse
Gas Inlet Temp. (^{o}F)	1025	760	580
Gas Outlet Temp. (^{o}F)	760	580	450
Gas Side Face Velocity (Ft/Sec)	55	45	39
Cmin/Cmax	0.85	0.84	0.83
Effectiveness	0.63	0.61	0.61

Table 1

Run 3 Hamilton Standard Matrices

Module	1	2	3
Module Identification	Fine	Fine	Coarse
Gas Inlet Temp. (^{o}F)	1050	770	600
Gas Outlet Temp. (^{o}F)	770	600	465
Gas Side Face Velocity (Ft/Sec)	50	42.5	37.7
Cmin/Cmax	0.30	0.31	0.30
Effectiveness	0.62	0.57	0.48

Run 4 Harrison Radiator Matrices

Module	1	2	3
Module Identification	Coarse	Fine	Coarse
Gas Inlet Temp. (^{o}F)	1025	832	700
Gas Outlet Temp. (^{o}F)	832	700	565
Gas Side Face Velocity (Ft/Sec)	51.2	45.9	42.1
Cmin/Cmax	0.92	0.91	0.91
Effectiveness	0.38	0.41	0.36

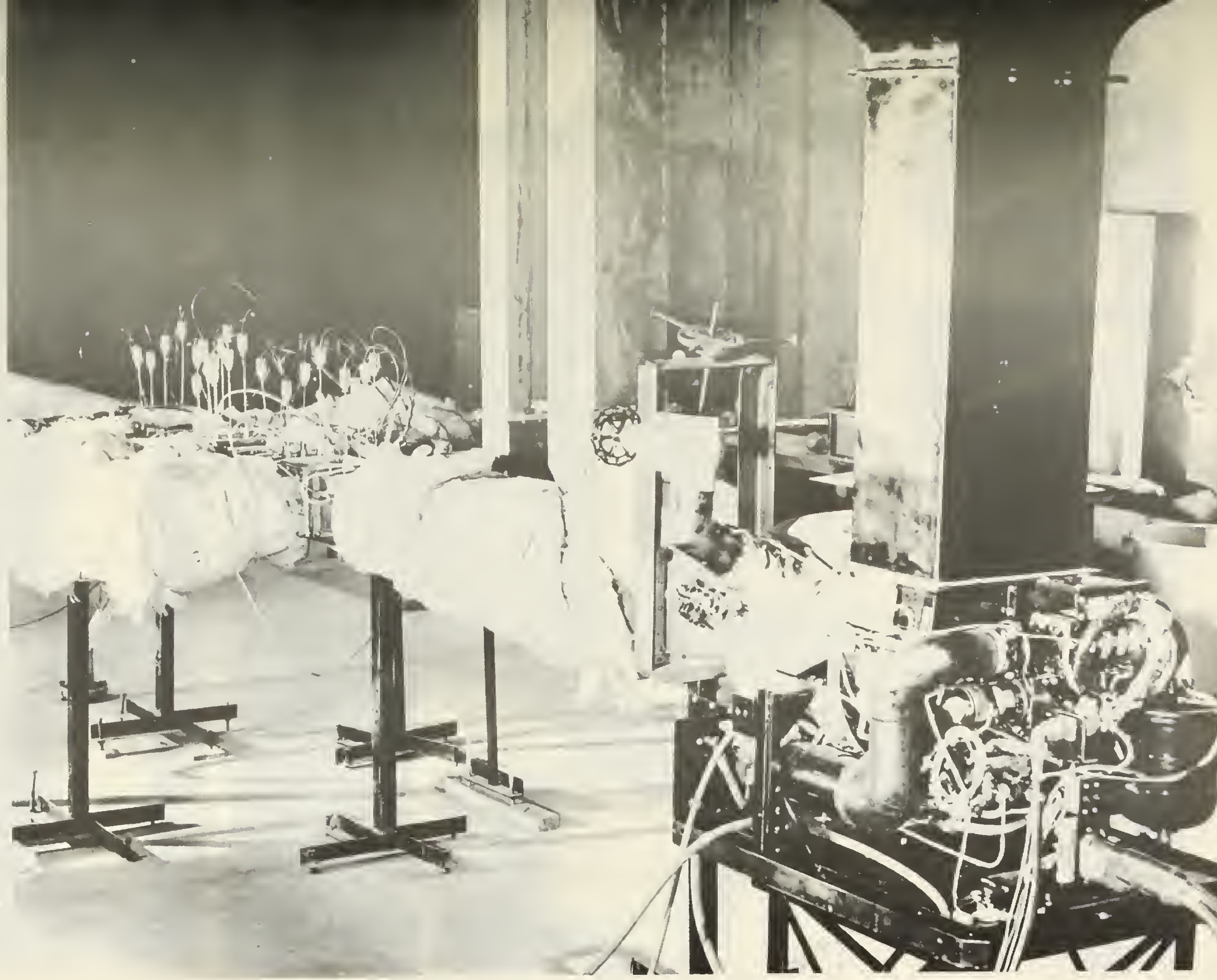


FIGURE 1. GENERAL VIEW OF TEST RIG.

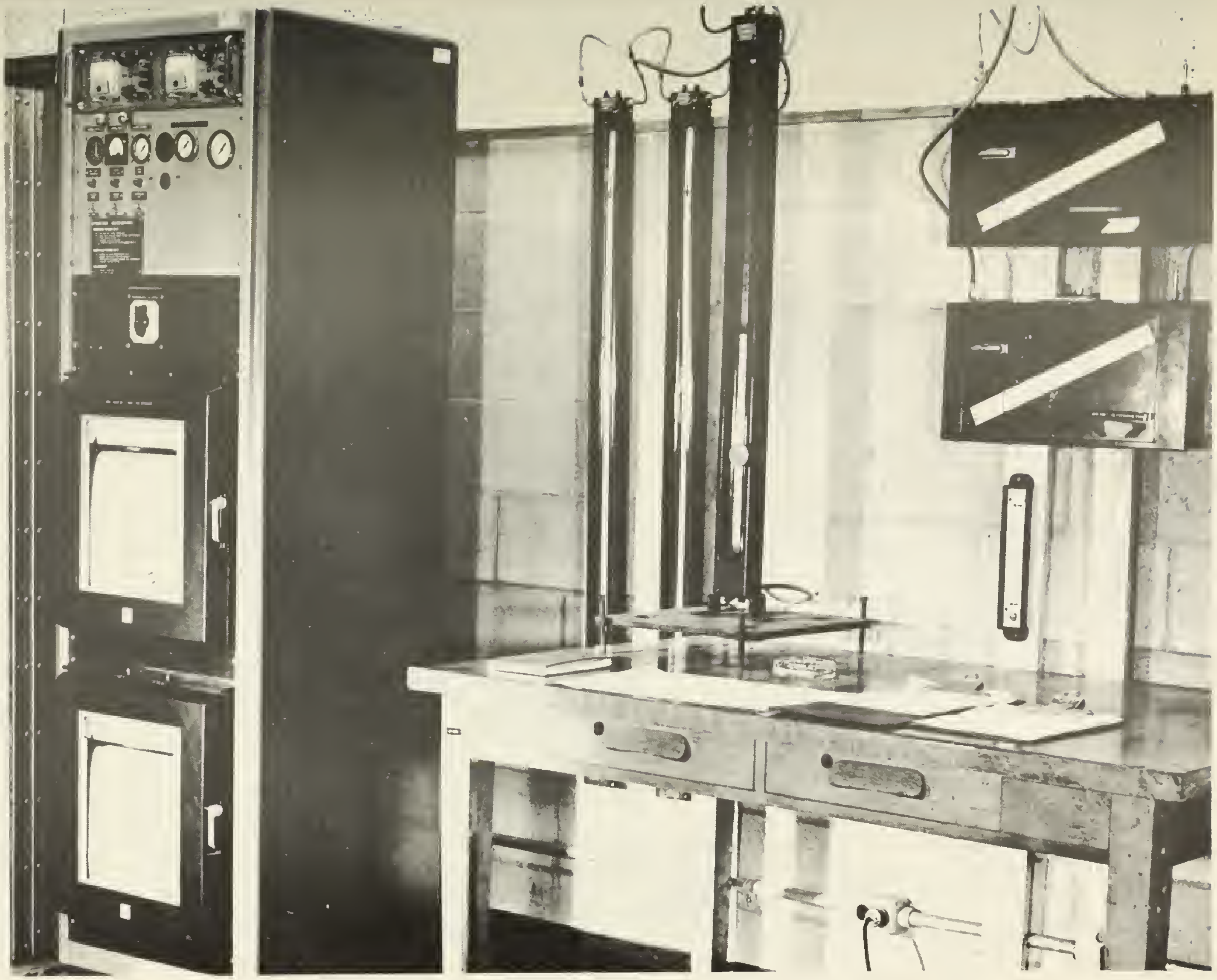
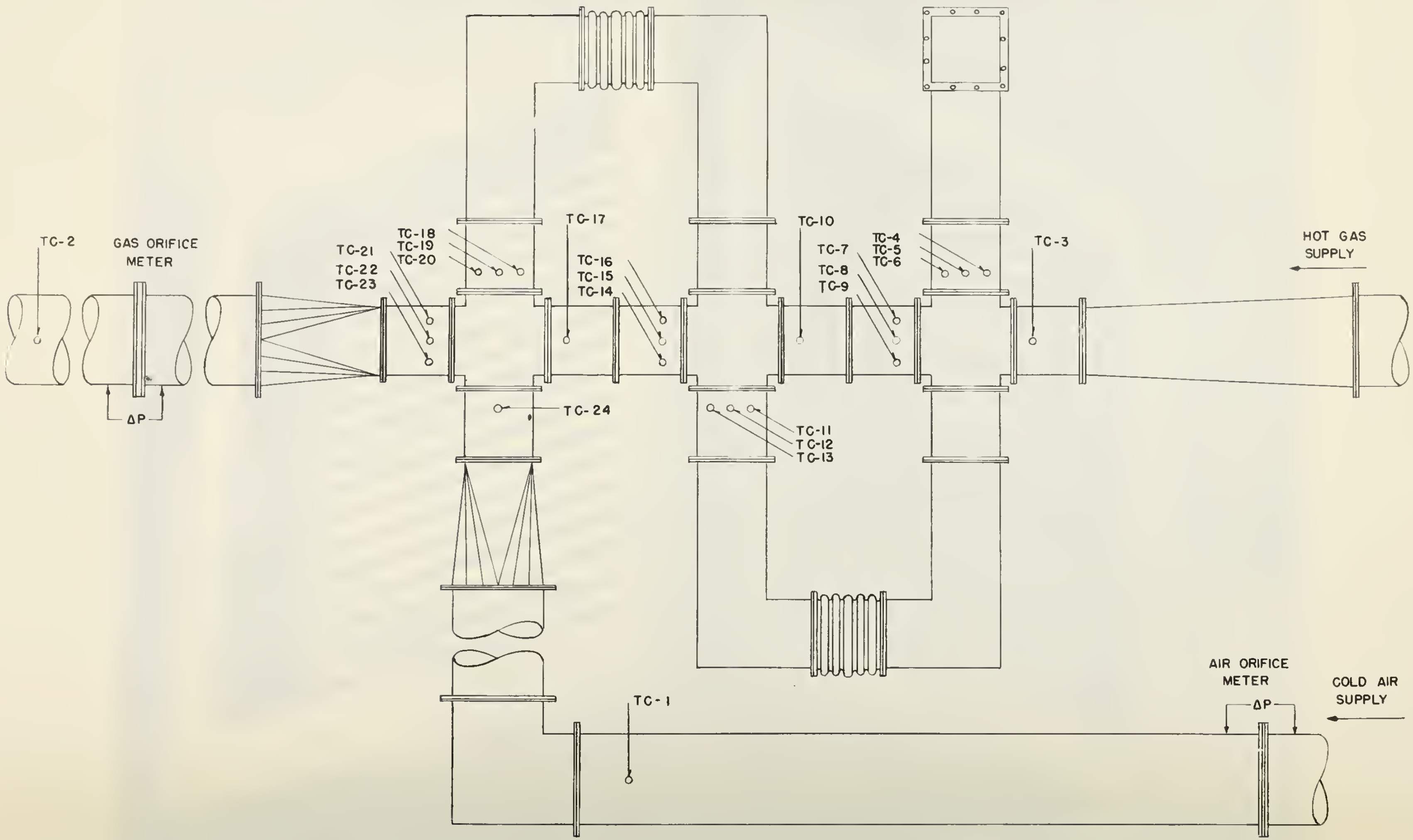


FIGURE 2. CONTROL PANEL AND INSTRUMENTATION.

FIGURE 3

LAYOUT AND INSTRUMENTATION - HEAT TRANSFER FOULING EXPERIMENT



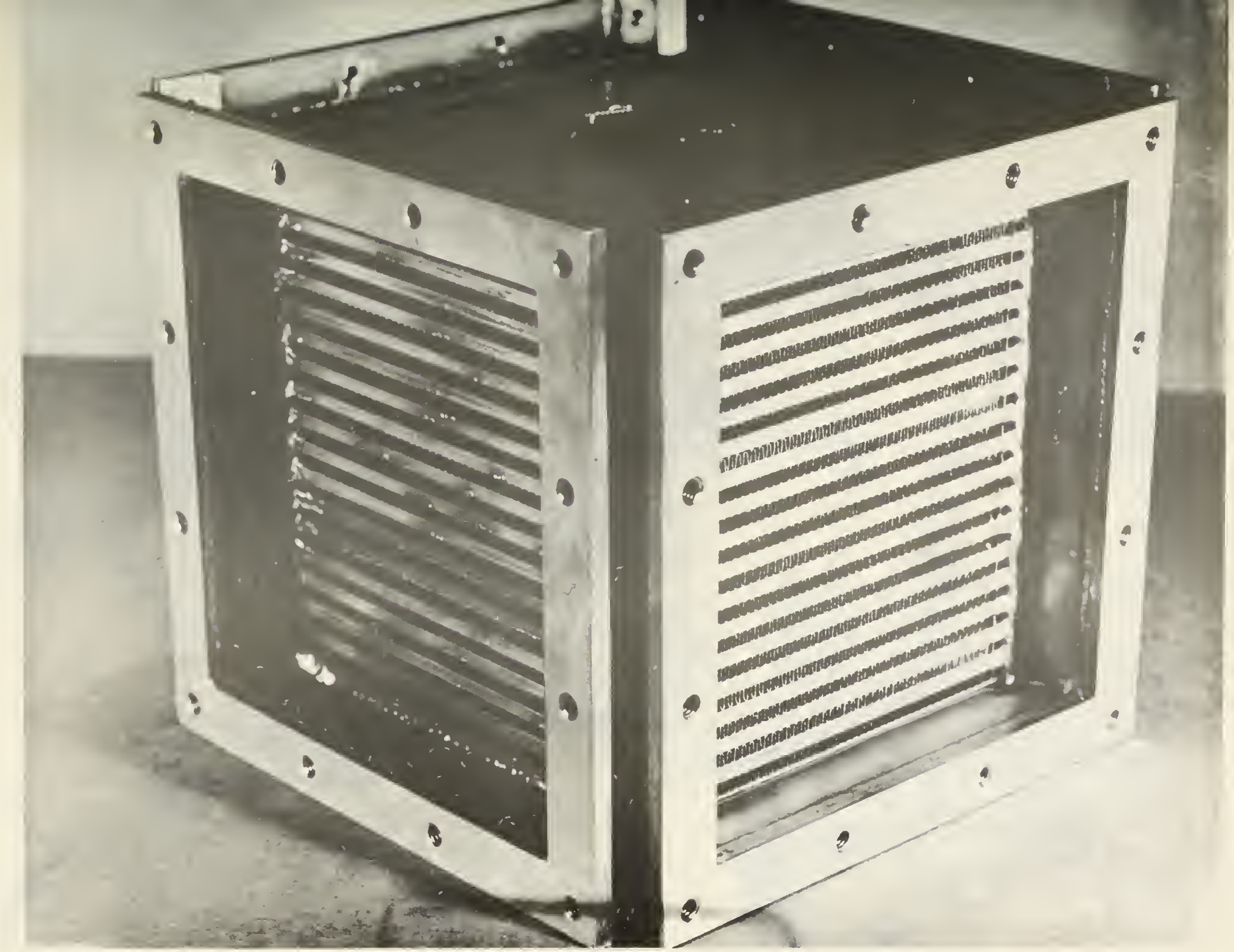


FIGURE 4. TYPICAL COMPACT CORE HEAT TRANSFER TEST MODULE.

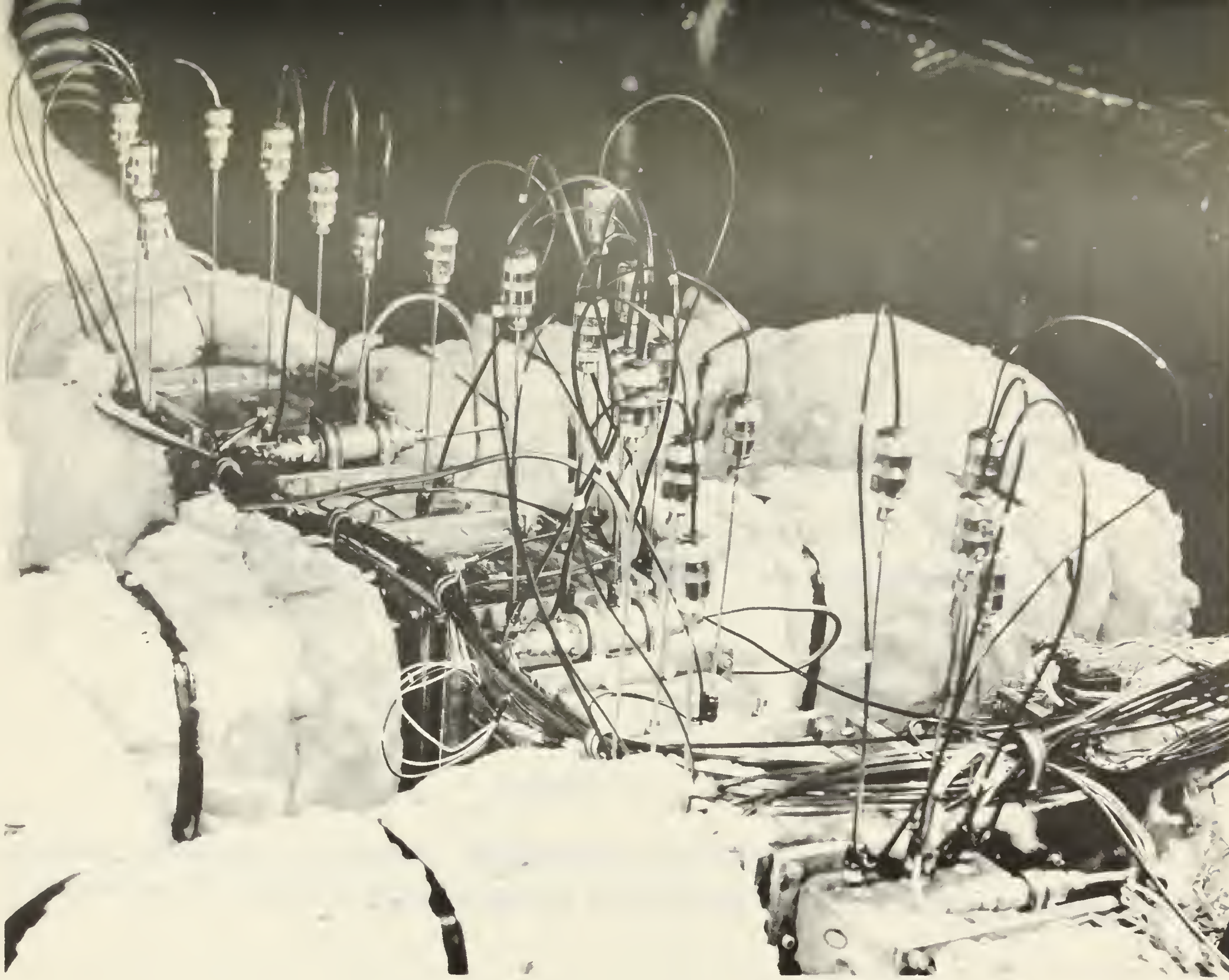


FIGURE 5. CROSS COUNTERFLOW INSTALLATION AND INSTRUMENTATION OF THREE TEST MODULES.

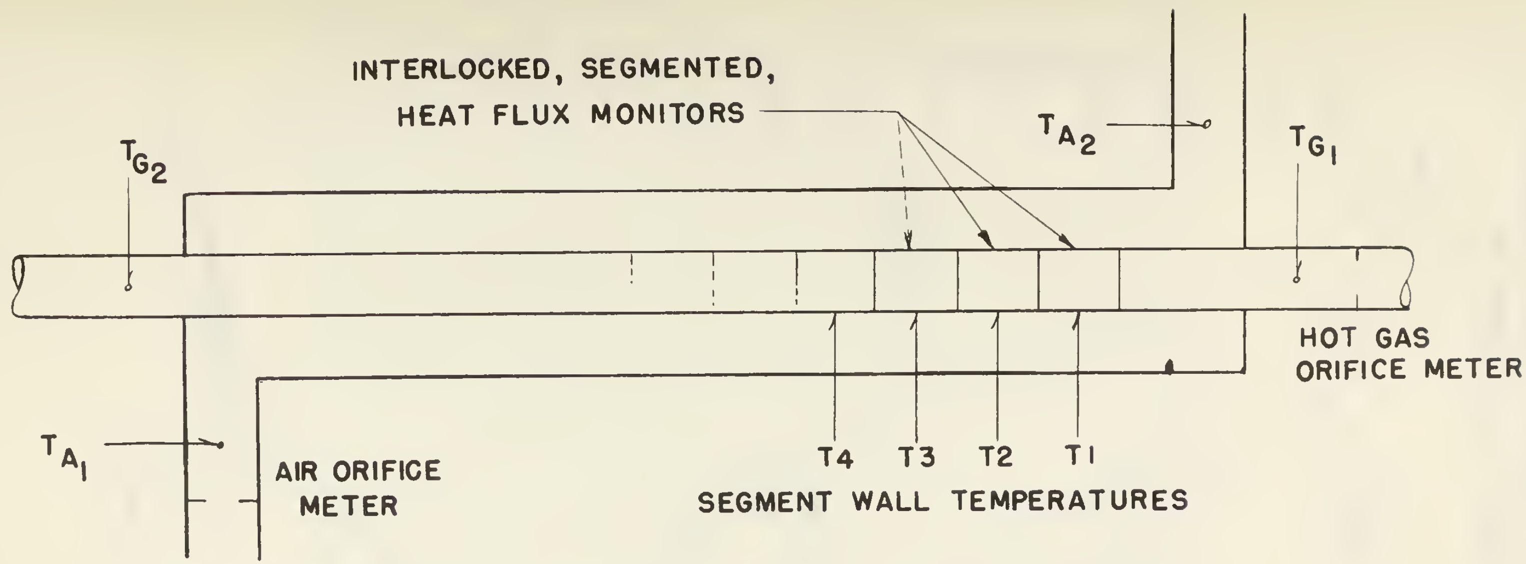


FIGURE 6

SCHEMATIC DIAGRAM OF A SIMPLE COUNTERFLOW HEAT EXCHANGER FOR THE EVALUATION OF FOULING DEPOSITION AS A FUNCTION OF WALL METAL TEMPERATURE

FIGURE 7

PRESSURE DROP AND HEAT TRANSFER CHARACTERISTICS OF OPERATING COMPACT CORES – RUN 1

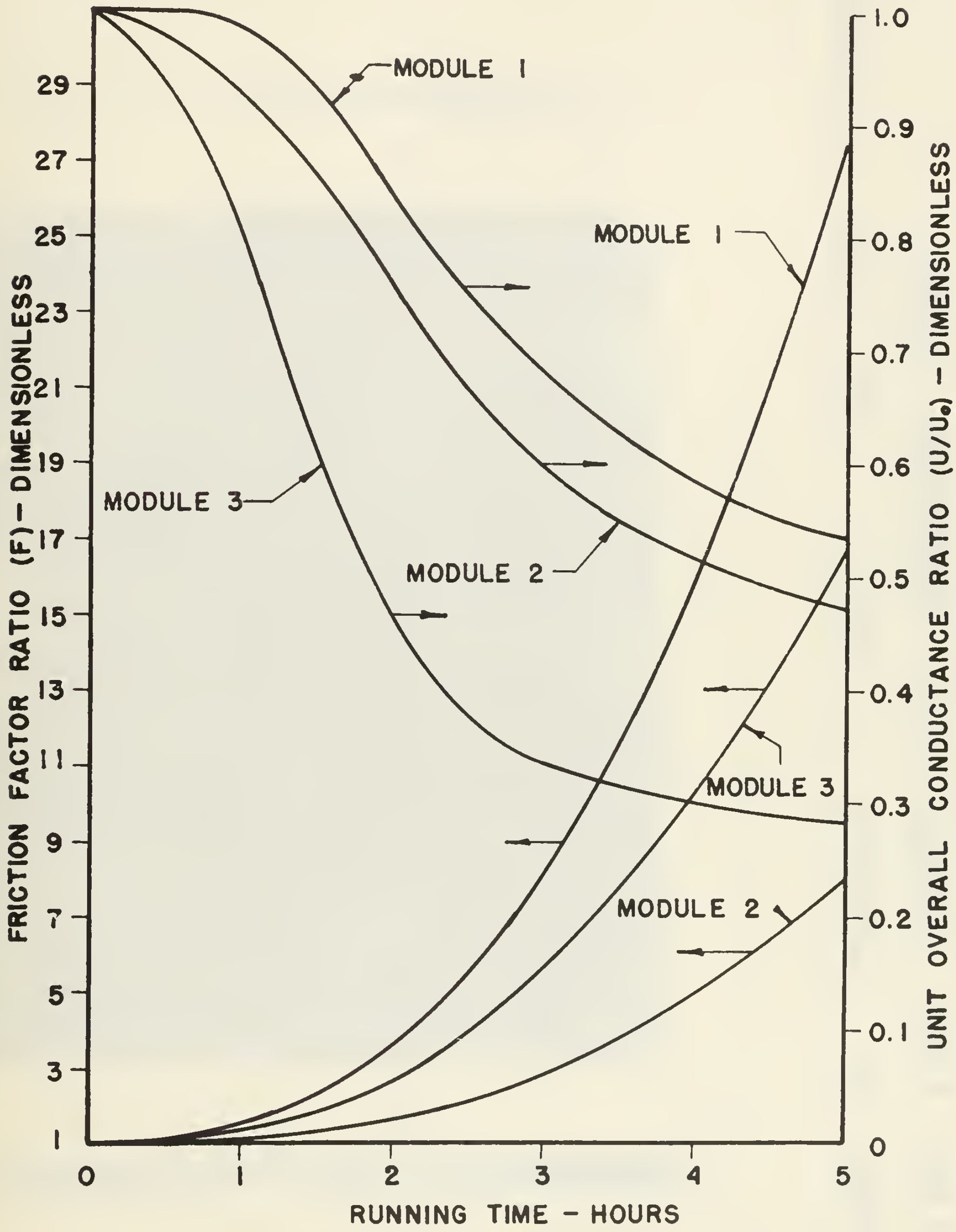


FIGURE 8. MODULE 1 RUN 1. GAS SIDE UPSTREAM AFTER FIVE HOURS OF RUNNING TIME.

FIGURE 9

PRESSURE DROP AND HEAT TRANSFER CHARACTERISTICS OF OPERATING COMPACT CORES — RUN 2

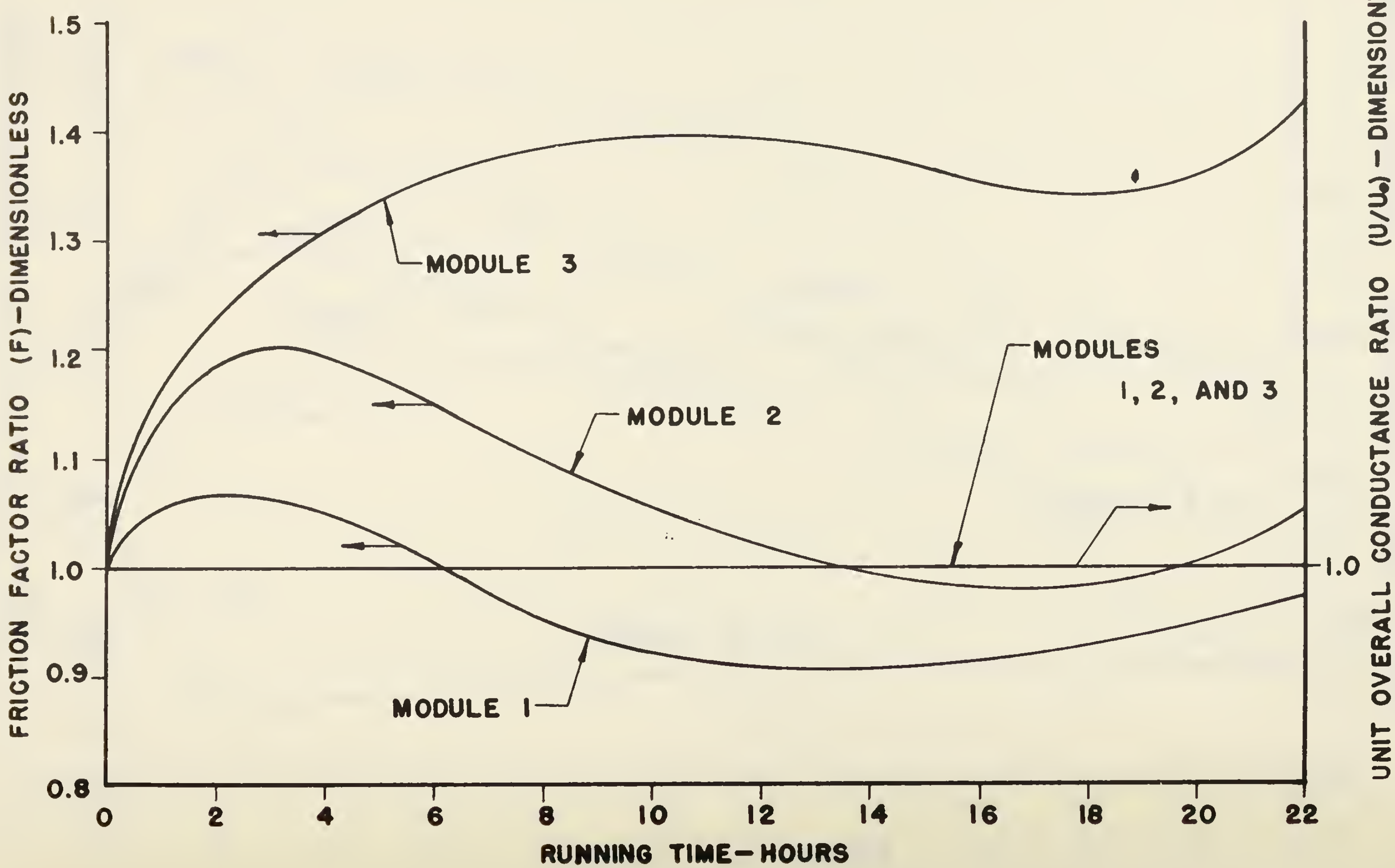


FIGURE 10

PRESSURE DROP AND HEAT TRANSFER CHARACTERISTICS OF OPERATING COMPACT CORES RUN 3

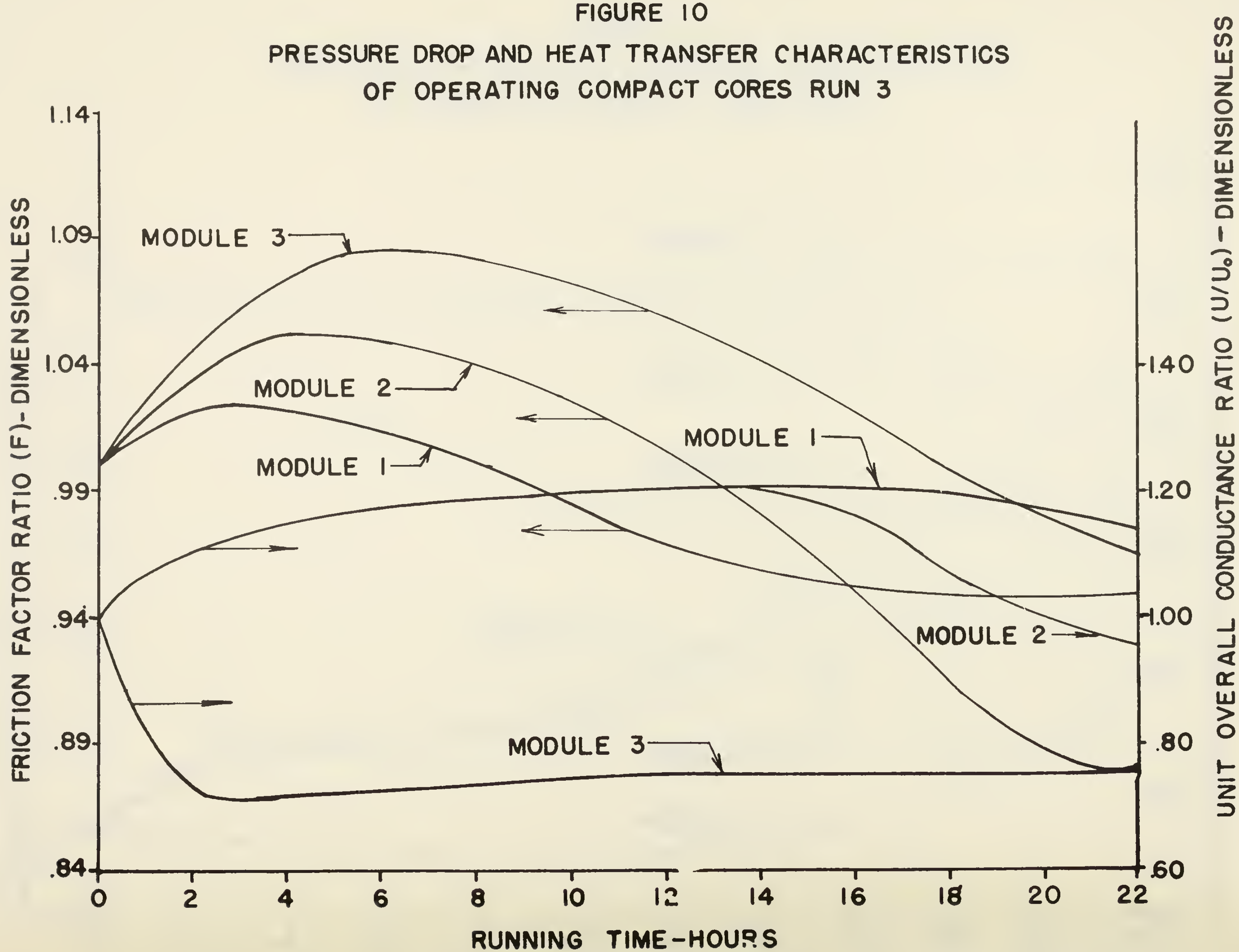
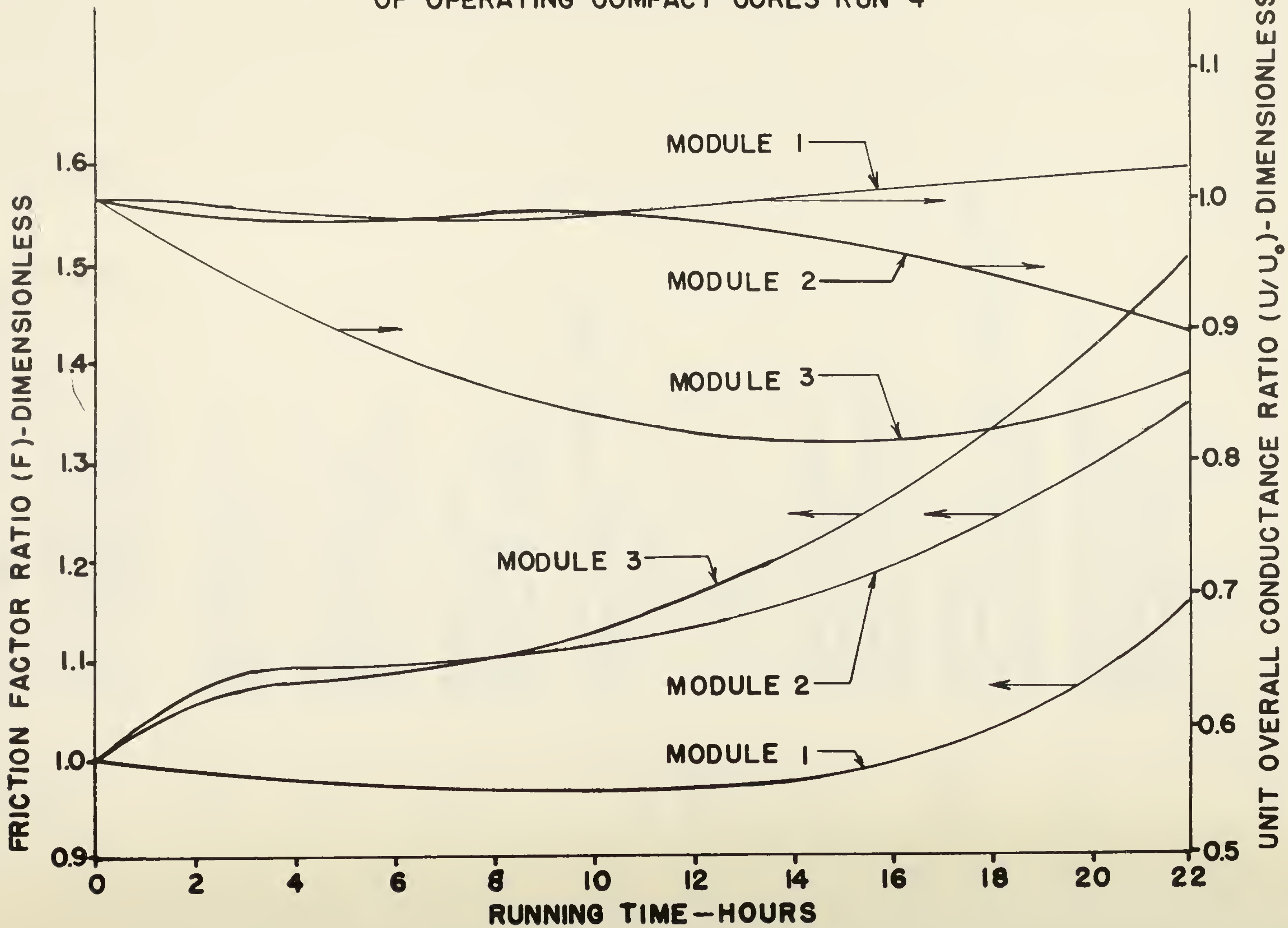


FIGURE 11

PRESSURE DROP AND HEAT TRANSFER CHARACTERISTICS OF OPERATING COMPACT CORES RUN 4



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